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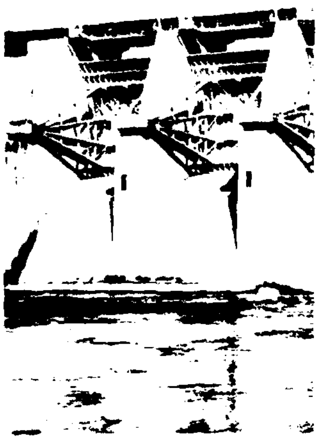

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LONG-TERM EFFECTS OF DREDGING
OPERATIONS PROGRAM

(2)

TECHNICAL REPORT D-88-9

REFINEMENT OF COLUMN SETTLING TEST PROCEDURES FOR ESTIMATING THE QUALITY OF EFFLUENT FROM CONFINED DREDGED MATERIAL DISPOSAL AREAS

by

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Column settling test procedures are used in designing confined dredged material disposal areas for effective sedimentation and initial storage of solids. This report presents the results of a study in which the test procedures were refined to allow a prediction of the effluent suspended solids concentration for conditions normally found when saltwater sediments are encountered. For this case, the dredged material normally settles by zone settling, forming a clarified supernatant in the confined disposal area. This study determined that the settling behavior of the fine particles initially remaining in the supernatant following zone settling is flocculent settling. Procedures were developed for predicting effluent concentrations as a function of retention time and other pertinent operating conditions. The ability to make such predictions is essential if total concentrations of contaminants in the effluent from confined disposal areas must be determined.

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PREFACE

This work was conducted as part of the Long-Term Effects of Dredging Operations (LEDO) Program by the Environmental Laboratory (EL), US Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss. The LEDO Program is sponsored by the Office, Chief of Engineers (OCE), US Army. This report was written as part of work unit 31775, "Techniques for Predicting Effluent Quality of Diked Containment Areas."

The work was performed by Dr. Michael R. Palermo, Research Civil Engineer, Environmental Engineering Division (EED), EL. Guidance and technical review for this work were provided by Dr. Palermo's dissertation research committee: Drs. Edward L. Thackston, Frank L. Parker, Peter G. Hoadley, Antonis D. Koussis, and Horace E. Williams, all of Vanderbilt University, and Dr. Robert M. Engler, Program Manager, Environmental Effects of Dredging Programs, EL. This report was written by Dr. Palermo and Dr. Thackston, who participated under an Intragovernmental Personnel Act (IPA) agreement. The work was performed under the general supervision of Dr. Raymond L. Montgomery, Chief, EED, and Dr. John Harrison, Chief, EL. Manager of LEDO within EL's Environmental Effects of Dredging Programs was Dr. Engler. The Technical Monitors for OCE were Dr. William L. Klesch, Dr. Robert W. Pierce, and Mr. Charles W. Hummer. The technical reviewers were Mr. Daniel E. Averett, Dr. Paul R. Schroeder, and Dr. F. Douglas Shields. This report was edited by Ms. Lee T. Byrne of the WES Information Products Division, Information Technology Laboratory.

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CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acres	4,046.873	square metres
acre-feet	1,233.489	cubic metres
cubic feet	0.02831685	cubic metres
feet	0.3048	metres
gallons (US liquid)	3.785412	cubic decimetres
inches	2.54	centimetres

REFINEMENT OF COLUMN SETTLING TEST PROCEDURES FOR ESTIMATING THE QUALITY OF EFFLUENT FROM CONFINED DREDGED MATERIAL DISPOSAL AREAS

PART I: INTRODUCTION

Background

1. The quality of effluent from confined disposal areas is strongly dependent on the concentration of total suspended solids in the effluent. Since most of the contaminants of interest are associated with particles, the concentration of suspended solids in the effluent will be a major factor influencing the total concentration of contaminants on a weight per unit volume basis. A modified elutriate test has been developed (Palermo 1984, 1986) that determines the concentration of dissolved contaminants and the contaminant fraction of the suspended solids likely to be present in the effluent. An accurate estimate of the concentration of suspended solids in the effluent must be made so that it can be used in conjunction with results of the modified elutriate test in order to predict the total concentration of contaminants in the effluent.

2. Montgomery (1978) developed procedures for estimating the total suspended solids concentration in confined disposal area effluents when the dredged material slurry exhibited a flocculent settling behavior. However, no procedures were proposed to allow prediction of the solids concentration in the effluent if the dredged material slurry exhibited a zone settling behavior. The settling behavior of the low concentrations of suspended solids (on the order of 100 mg/ℓ) in the semi-clarified water above the interface for this settling case was not known at that time.

3. When slurries undergo zone settling in a laboratory test column, almost all of the solids are entrapped in a loose open matrix that settles as a single mass. However, a few colloidal solids that are not trapped in the matrix remain in the semi-clarified supernatant above the interface. In addition, as the mass settles, it displaces water from below, which must move upward through the voids in the settling mass. This upward water velocity shears some loosely bound colloids from the settling mass and carries them

into the supernatant, causing the suspended solids concentration to rise in the initial stages. Higher slurry concentrations produce smaller void spaces and higher resulting upward water velocities, causing more solids to be carried into the semi-clarified supernatant. In addition, under field conditions, wind and advective flow generate turbulence that inhibits sedimentation and resuspends some solids, increasing the effluent suspended solids concentration above that predicted by a quiescent laboratory column settling test.

4. Montgomery (1978) did not propose any method of quantifying the suspended solids concentration in the supernatant, which in a confined disposal area becomes the effluent concentration. He stated only that the concentration should be below 1 to 2 g/ℓ, low enough to satisfy most of the effluent discharge permit standards common at that time. However, today, with many discharge permits limiting suspended solids concentrations in the effluent to below 0.1 g/ℓ, this approach is not sufficient. Therefore, Palermo (1984, 1986) devised a method to predict the suspended solids concentration in the supernatant as a function of retention time, based on the results of the laboratory flocculent settling test.

Purpose and Scope

5. The objective of this study was to develop a technique that could be used to predict the suspended solids concentration in the effluent from a confined disposal area in which the bulk of the slurry mass settled by zone settling. The work involved a modification of the column test procedures developed by Montgomery (1978) and the development and verification of appropriate methods of data analysis.

6. Procedures were designed to be as simple as possible, while still remaining soundly grounded in fundamental principles and being able to produce reliable, accurate results. They were also designed to simulate actual field conditions as closely as possible.

7. This technical report includes a description of the experimental work, a description of the experiments conducted to verify the applicability of the predictions to actual field conditions, an outline of the recommended procedures, and an example illustrating the use of the procedures. The procedures can now be used by US Army Corps of Engineers field offices and permit applicants in the evaluation of confined dredged material disposal activities.

PART II: DREDGED MATERIAL SETTLING

Types of Settling

8. This background material will be familiar to the civil or chemical engineer who has advanced training in physical/chemical water treatment process design, but not to most general civil engineers. Therefore, it is provided as an aid to understanding the descriptions of the tests and the rationale behind the decisions and choices that were made in the development of the procedure.

9. Four different types of settling are generally recognized. The type that occurs in any given suspension is a function of both the type of particle involved, particularly its surface characteristics, and the concentration of particles at a given time. The four types are listed below:

- *a*. Discrete settling (Type I). The particle does not interact during settling. Each particle maintains its individuality and does not change in size, shape, or density while settling. Each particle settles as if it were alone and isolated.
- *b*. Flocculent settling (Type II). The particles flocculate and agglomerate during settling. As the particles grow in size, they decrease in density because of entrained water, but they usually settle faster.
- *c*. Zone settling (Type III). The concentration of particles is so great that they touch adjacent particles in all directions and maintain their spatial relationship, settling as a mass or open matrix. They usually exhibit a definite interface between the settling particles and the clarified liquid above. The particle matrix settles more slowly than the individual particles of the same size and density because the quantity of water being displaced by the settling particles is so great that the resulting upward velocities of the displaced water reduce the effective downward velocity of the particle mass.
- *d*. Compression settling (Type IV). The concentration is so great that the particles rest on each other and mechanically support each other. The weight of the particles above slowly compresses the lower layers, increasing the pore pressure and squeezing out the water. This is also sometimes called thickening or compaction. In water treatment plants, the settling is sometimes aided by slow stirring to break up the bridging action of the particles, but this is impossible in confined disposal areas, which must rely on gravity alone.

10. The relation of the different types of settling to type of particle and concentration of particles is shown in Figure 1.

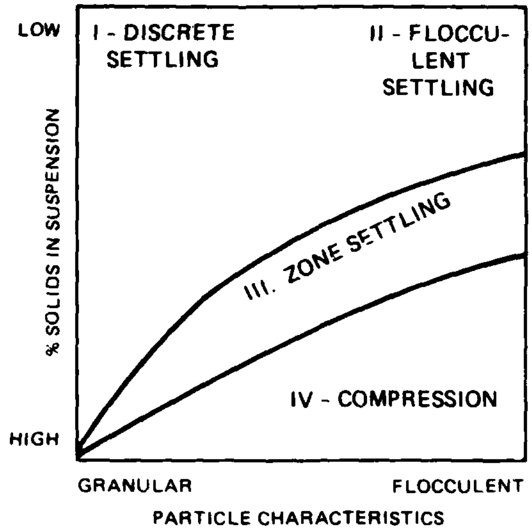

Figure 1. Types of settling

Dredged Material Settling Processes

11. From Figure 1 it can be seen that discrete settling occurs only in suspensions with low concentrations of granular particles. This occurs in a confined disposal area only with the small fraction of larger particles (sand and gravel) occasionally encountered and with intrusions such as bricks, crockery, shells, broken tools, and household items that were thrown or washed into the waterway. It never occurs with hydraulically placed fine-grained dredged material, because the concentrations of the influent are so high (50 to 200 g/ℓ) and because most of the particles (clay, silt, organic matter) are naturally flocculent. All of the other three settling processes may occur simultaneously in a confined disposal area, and any one may control the design of the confined disposal area.

12. Dredged material slurries will initially exhibit either flocculent settling or zone settling, depending primarily on the slurry concentration, particle type, and salinity of the water. Saline slurries with salinity greater than 3 ppt will usually exhibit zone settling, because the dissolved ions act as a coagulant. These ions compress the electrical double layer, reduce the effective distance over which the natural repulsive surface forces are effective, and allow sediment particles to touch enough adjacent particles that a loose open matrix is formed, which settles as a mass. Freshwater

slurries usually exhibit flocculent settling, but may exhibit zone settling if concentrations are high enough or if the particle surface characteristics are flocculent enough.

13. Regardless of whether the upper layers of the containment area initially exhibit flocculent or zone settling, the lowest layers will exhibit compression settling, or thickening. When the slurry approaches the bottom and the concentration rises, successive layers will begin to rest on and be supported by the bottom and then each other, much like an accordion being slowly lowered onto a hard surface. The change from flocculent or zone settling to compression settling, at which the bottom begins to provide some physical support, occurs at a concentration of approximately 200 to 300 g/ℓ for most dredged material slurries.

PART III: REFINEMENT OF PROCEDURES FOR PREDICTING EFFLUENT SUSPENDED SOLIDS

Modification of Column Settling Test Procedure

14. McLaughlin (1959) developed procedures to determine the settling regime (discrete, flocculent, or zone) of slurries. A series of laboratory settling tests using McLaughlin's procedures was conducted on representative fine-grained sediments to investigate the settling regime of the supernatant.

15. The 8-in.* settling column previously recommended for confined disposal area design (Montgomery 1978; Palermo, Montgomery, and Poindexter 1978) was used to conduct settling tests on sediments from Mobile Harbor, Alabama (composite); Black Rock Harbor, Connecticut; and Yellow Creek, Mississippi. Generally, the standard testing procedure described by Montgomery for freshwater sediment was used. However, when zone settling of the slurry was observed, with a clearly defined interface, samples were taken from side ports above the interface. This procedure had not previously been performed.

16. The tests were conducted by mixing the sediment and water from the dredging site to concentrations within the range expected for disposal area influents. The slurry was then placed in the columns and allowed to settle. For those sediments in which an interface formed, a sample of the supernatant was taken from the uppermost port as soon as the settling interface fell below the port far enough to allow sample withdrawal without disturbing the interface. For all tests, this occurred within a few hours of the initiation of the test. Samples were then taken from all ports above the falling interface at time intervals of approximately 6, 12, 24, 48, and 96 hr, continuing to 15 days or until the supernatant suspended solids concentration indicated essentially no further removal of suspended solids through sedimentation. The port samples were analyzed for concentration of total suspended solids in the supernatant.

17. The Yellow Creek sediment was from a freshwater environment, and the tests were run at initial slurry concentrations of 33 and 148 g/ℓ. Mobile

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

Harbor and Black Rock Harbor sediments were from saltwater environments, and a range of initial slurry concentrations was tested. Additional tests were also later run using Mobile Harbor sediment to check the reproducibility of results.

Settling Regime of Supernatant Suspended Solids

18. The samples from the upper sampling ports made possible the determination of settling behavior in the supernatant using the graphical procedure of McLaughlin (1959). McLaughlin describes the use of concentration profile diagrams for analysis of quiescent settling test data. The fraction of suspended solids remaining in a suspension, $\phi(z,t)$, is plotted versus the depth below the fluid surface, z , for various sampling times, t , as shown in Figure 2, and smooth curves are drawn through the data points, as illustrated by the solid lines on Figures 2 through 4.

19. One will note that, in Figures 2 through 4, all of the ϕ versus z lines go through the origin. In other words, there is a zero solids concentration at zero depth at any time greater than zero. This boundary condition, originally stated by McLaughlin (1959), was justified on the

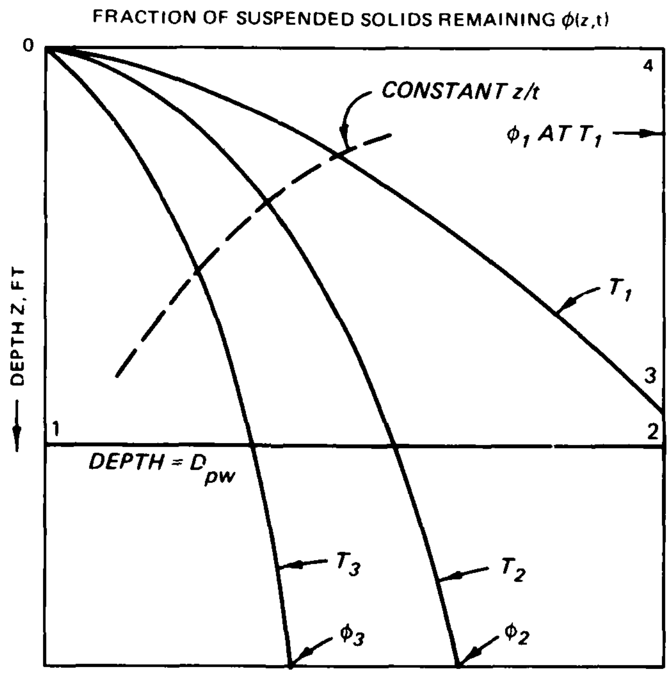

Figure 2. Typical concentration profile diagram

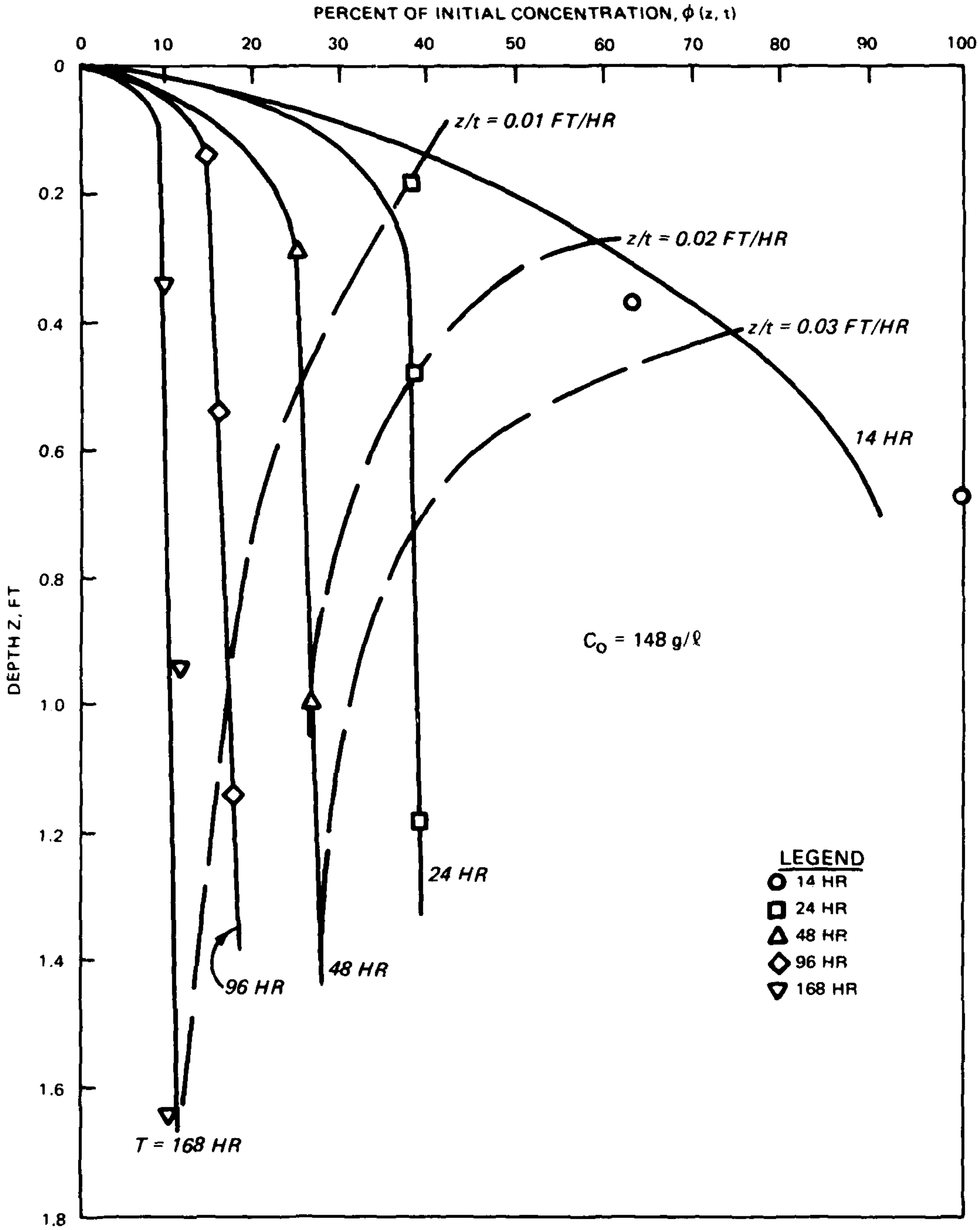

Figure 3. Concentration profile diagram for particles above the interface for Yellow Creek sediment

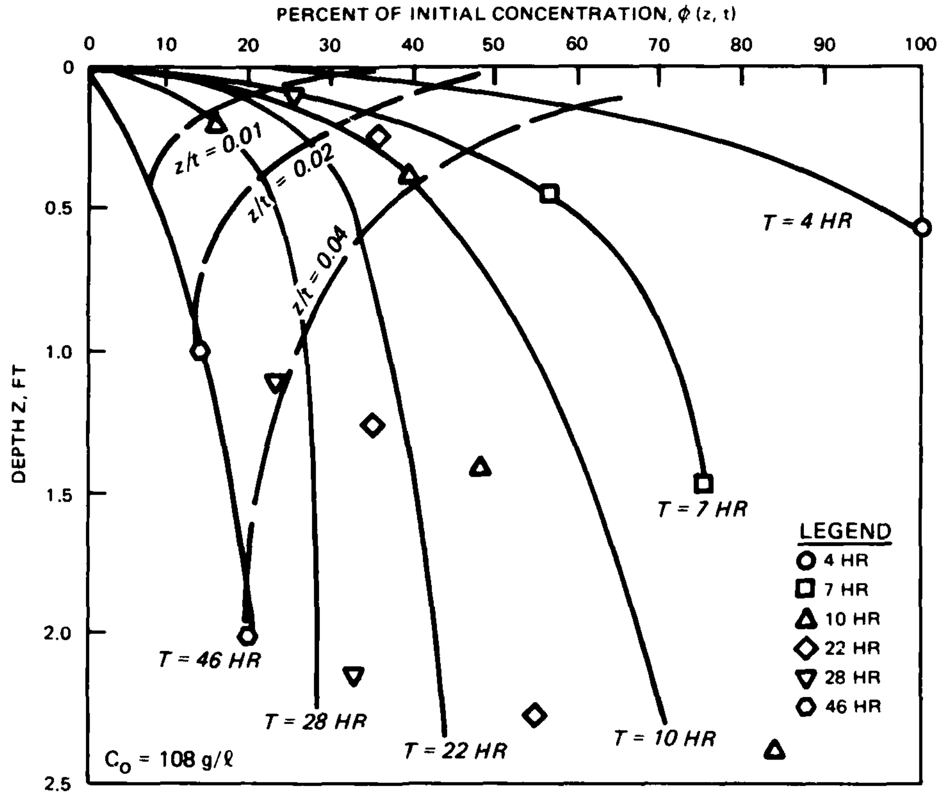

Figure 4. Concentration profile diagram for particles above the interface for Mobile Harbor sediments (composite)

grounds that, after any finite time, gravity will cause even the smallest particles to settle some small distance away from the surface. However, Brownian motion effects, air currents, thermal currents, currents caused by hindered settling, and other similar effects will cause some suspended solids to remain in suspension at or near the surface for long periods of time in a real situation. This causes some difficulties in fitting smooth curves of continuous mathematical functions through all points and in extrapolating them to the surface and to the interface.

20. A digital computer program fit a continuous function to the data points and computed the areas by numerical integration to determine the removal percentages. The available equations are not always able to closely fit all of the data points and also have the concentration at the surface decrease continuously as a function of time. The curves do not really go through the origin, because the low concentrations of colloidal solids

remaining in the supernatant after several hours of settling are not controlled primarily by gravity forces and are as likely to be very near the surface as anywhere else.

21. The experience of this project generally showed that:

<u>a</u>. The lines were usually concave downward, even if only very slightly.

<u>b</u>. The lower portion of the line was sometimes almost straight and almost vertical, but always sloped slightly away from the left margin at higher values of z.

<u>c</u>. The curves rarely if ever reversed direction.

<u>d</u>. Curvature was usually much greater near the surface than at greater depths.

22. A family of lines of equal z-to-t ratio can also be constructed. Such curves represent the concentration as seen by an observer by starting at the surface of the suspension at initial $t = 0$ and descending at constant velocity. (These are the dashed lines on Figures 2 through 4.) McLaughlin (1959) observed that when neither hindered nor flocculent settling is occurring, a line of constant z/t is straight and parallel to the z-axis. If flocculent settling occurs, the z/t line slopes toward the z-axis (converges at higher z values) as shown in Figure 2. If hindered settling occurs, the line slopes away from the z-axis (diverges at higher z values).

23. The Yellow Creek sediment was from a freshwater environment, and the entire slurry initially exhibited flocculent settling behavior. An interface was then observed to form about 10 hr after the initiation of the 148-g/ℓ test. As expected, the analysis of samples taken above the interface also showed that these solids exhibited flocculent behavior. The concentration profile diagram for samples taken above the interface is shown in Figure 3. Results for the 33-g/ℓ test were similar. Note that Figure 3 was constructed with $\phi = 100$ percent corresponding to the initial sample taken from the uppermost port. The rationale for this approach is discussed in detail in later paragraphs.

24. The Mobile Harbor and Black Rock Harbor sediments are from saltwater environments. The slurries exhibited zone settling behavior at the concentrations tested, with clearly defined interfaces forming between the supernatant and the more concentrated slurry. However, the concentration profile diagram indicates that the solids remaining in the supernatant exhibited flocculent settling for all initial concentrations tested. A representative

concentration profile diagram for the Mobile Harbor tests is shown in Figure 4. All z/t curves converge with the z-axis at higher z values. Results for other concentrations in the Mobile Harbor and Black Rock Harbor tests were similar. These data indicated that flocculent settling occurs at concentrations below 100 mg/ℓ for fine-grained dredged material.

Refined Prediction of Effluent Suspended Solids Concentration

Data analysis

25. The flocculent settling behavior exhibited in supernatant water greatly simplified the development of an appropriate method for data analysis and prediction of effluent suspended solids concentrations. McLaughlin (1959) utilized a graphical approach for flocculent settling data analysis using the concentration profile diagram to compute the removal ratios for any given retention time. A modification of this approach was developed to allow computation of the concentration of suspended solids in the supernatant of the column tests, and consequently, the prediction of suspended solids concentrations in the effluent from the confined disposal area.

26. The procedure involves the determination of areas to the left and right of the concentration profile line for a given retention time. The areas are determined using the zero concentration and the initial concentration of the test as the left and right vertical boundaries, and the zero depth and a specified depth of averaging as the top and bottom horizontal boundaries. The area to the right of the curve (area 0, 3, 4, 0 in Figure 2) divided by the total area (area 0, 1, 2, 4, 0 in Figure 2) when multiplied by 100 will equal the suspended solids removal percentage, R_t , at time T through the depth, D_{pw} . The percentage of initial solids remaining at time T, P_t is simply $100-R_t$. P_t is a depth-integrated value over the depth of averaging under consideration.

27. This approach can be directly applied for the case of flocculent settling of the entire slurry mass, as recommended by Montgomery (1978). However, for the case of zone settling of the slurry mass, the McLaughlin (1959) approach must be applied only to the flocculent settling regime in the clarified water above the interface. An initial sample can be taken only when the settling interface clears the uppermost port. If the suspended solids

concentration in this sample is assumed to be $\emptyset$ = 100 percent , the removal percentage, R_1 , and the percentage remaining, P_1 , at T_1 may be calculated. The computation of subsequent removal ratios and percentages at other retention times can be accomplished in a similar manner. These data may be used to develop a relationship between removal percentage versus time as described by Montgomery (1978), or as suspended solids concentrations remaining versus time. The sensitivity of the results to the assumed initial concentration of suspended solids, initial slurry concentration, and depth of averaging are discussed below.

Effect of initial supernatant suspended solids concentration

28. To develop a concentration profile diagram, the removal percentages must be expressed in terms of some initial concentration. McLaughlin (1959) used the true initial concentration, but for the zone settling supernatant, this is not measurable, so some initial concentration of supernatant suspended solids must be assumed. The effect of the assumed initial suspended solids concentration can be shown using the results from the Mobile Harbor test run at an initial slurry concentration of 108 g/ℓ. An initial sample of the supernatant was taken when the falling interface cleared the uppermost port at T = 4 hr. The concentration of this sample was 110 mg/ℓ. The concentration profile diagram for this test is shown in Figure 4 with $\emptyset$ = 100 percent corresponding to 110 mg/ℓ. It is obvious that the measured value at 4 hr is not a true value of initial suspended solids concentration in the supernatant. However, using the first measurement as the reference value is convenient for purposes of data analysis. Also, any higher value representing an earlier time that could be calculated by some extrapolation method would have little theoretical or practical advantage, since a few hours would be necessary for sufficient supernatant volume to develop for flocculent settling processes to begin.

29. The sensitivity of this assumption was shown by comparing relationships of total suspended solids remaining versus time calculated using various values for the initial concentration. Table 1 summarizes the data for an initial suspended solids concentration of 110 mg/ℓ (the first real measurement) and assumed values of 150 and 200 mg/ℓ. The graphical determinations of removal percentages were made using the general procedure as described previously, with the assumed value for initial concentration used to construct

Table 1

Supernatant Suspended Solids Remaining for Various Assumed Initial Supernatant Suspended Solids Concentrations Mobile Harbor Sediment, Initial Slurry Concentration 108 g/ℓ, Depth of Averaging 1 ft

	Assumed Initial Concentration in Supernatant					
	110 mg/ℓ		150 mg/ℓ		200 mg/ℓ	
Time hr	Removal Percentage	Remaining SS* (mg/ℓ)	Removal Percentage	Remaining SS (mg/ℓ)	Removal Percentage	Remaining SS (mg/ℓ)
4	15	94	34	99	51	98
7	46	59	62	57	71	58
10	60	44	72	42	79	42
22	76	26	83	25	87	26
28	87	14	90	15	93	14
46	91	10	94	9	95	10

* SS = suspended solids.

concentration profile diagrams with $\emptyset$ = 100 percent corresponding to the assumed initial concentration. The graphical determinations were made for D_{pw} = 1.0 ft. The total suspended solids values were then calculated for each time by multiplying the percentages remaining by the assumed initial concentration. Exponential curves were fit to the data and are shown in Figure 5. These curves indicate essentially no effect due to the different assumed values for initial suspended solids in the supernatant. This occurred because the assumed initial concentrations greater than the first measured value of 110 mg/ℓ placed the $\emptyset$ = 100 percent vertical boundary for the graphical procedure well to the right of the concentration profiles. The areas bounded by the removal curves and thus the computed concentrations remaining were therefore not substantially changed. It is therefore recommended that the measured suspended solids concentration in the first port sample be used as the initial concentration for purposes of future data analysis.

Effect of depth of averaging on concentrations remaining

30. Under quiescent settling conditions, the percentage of suspended solids remaining in the supernatant water increases with the depth of

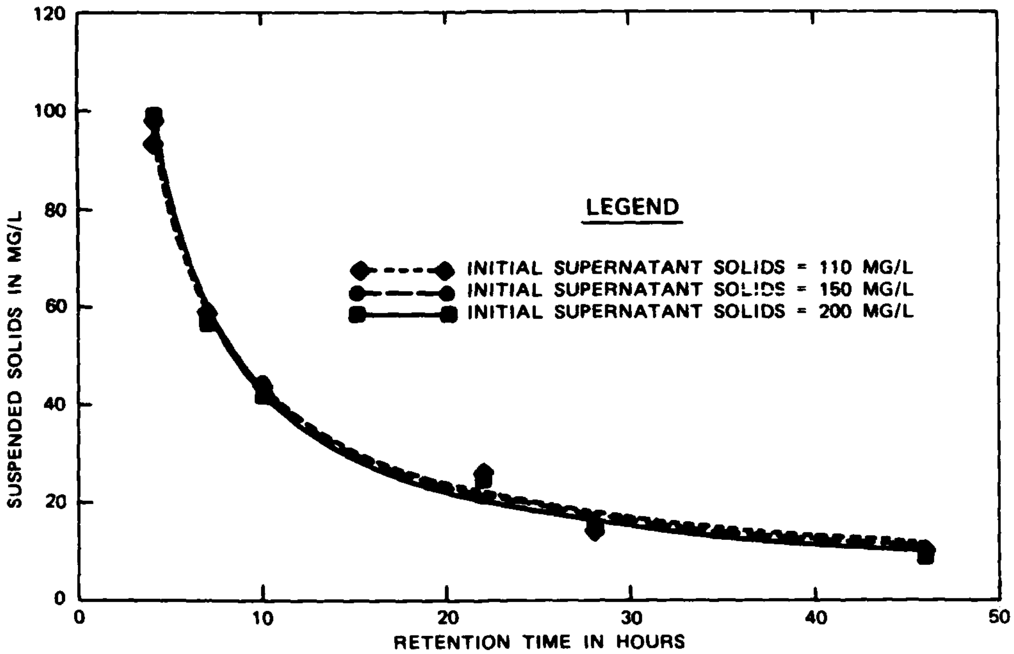

Figure 5. Relationship of predicted effluent suspended solids concentration versus time for various assumed initial supernatant concentrations, Mobile Harbor column test

averaging and decreases with time. This is clearly indicated by the shape of the concentration profile diagrams. The sensitivity of the predicted remaining suspended solids concentration to this variable was shown by comparing relationships of total suspended solids versus time for several depths of averaging, using the results from the same Mobile Harbor test with an initial slurry concentration of 108 g/ℓ. Table 2 summarizes the data for depths of averaging of 1, 2, and 3 ft. The data were calculated using the first port measurement as the initial concentration, as recommended above. Curves were fit to the data as described above, and they are shown in Figure 6. The comparison shows that, for a given retention time, the suspended solids remaining increase as the depth of averaging increases. For example, at a retention time of 20 hr, the predicted concentration increases from approximately 25 to 40 mg/ℓ as the depth of averaging increases from 1 to 3 ft. This magnitude of difference shows that the depth of averaging must be carefully considered in the prediction of effluent concentrations using column test results.

31. The appropriate depth of averaging for use in prediction should be the best estimate of the depth of influence of the discharge weir of the

Table 2

Supernatant Suspended Solids Remaining for Various Depths of Averaging, Mobile Harbor Sediment, Initial Slurry Concentration 108 g/ℓ, Initial Supernatant Suspended Solids Concentration 110 mg/ℓ

	Depth of Averaging					
	1.0 ft		2.0 ft		3.0 ft	
Time hr	Removal Percentage	Remaining SS* (mg/ℓ)	Removal Percentage	Remaining SS (mg/ℓ)	Removal Percentage	Remaining SS (mg/ℓ)
4	15	94	8	101	5	105
7	46	59	36	70	31	76
10	60	44	49	56	42	64
22	76	26	69	34	61	43
28	87	14	79	23	75	28
46	91	10	87	14	84	18

* SS = suspended solids.

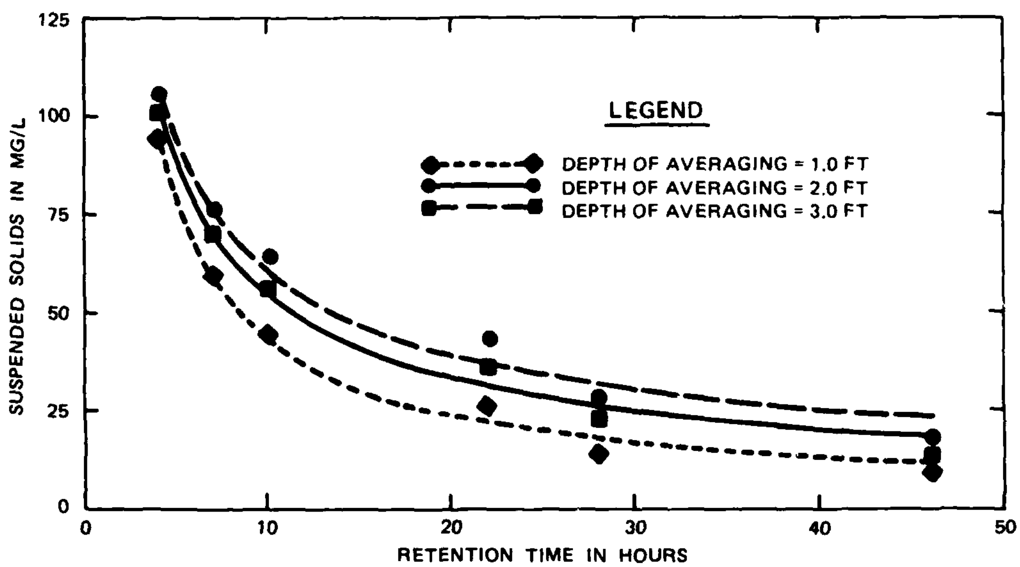

Figure 6. Relationship of predicted suspended solids concentration versus time for various depths of averaging, Mobile Harbor column test

confined disposal area under field conditions. The effluent discharged from a confined disposal area will contain suspended solids that are drawn from the ponded water in the disposal area. The depth of influence from which water is withdrawn is governed by the characteristics of the weir structure and the flow rate and ponded conditions within the disposal site, especially near the weir.

32. Walski and Schroeder (1978) showed that the depth of the withdrawal zone or depth of influence is highly dependent on the density gradient of the fluid in the pond. For a dredged material undergoing zone settling, there is a clearly defined interface between settled material and supernatant water, essentially forming a two-zoned system. Field data collected by Walski and Schroeder (1978) indicated that the depth of influence for this case is essentially equal to the ponded depth, or depth to the interface. It is therefore recommended that the assumed depth of averaging used in the prediction of effluent suspended solids be selected as that equal to the anticipated depth of ponding at the weir structure. An exception could occur in the case of a confined disposal area with great depth, low discharge rate, and long discharge weir.

Effect of initial slurry concentration

33. Montgomery (1978) showed that zone settling velocity was a function of the concentration of the slurry tested. The effect of initial slurry concentration on concentrations of suspended solids remaining in the supernatant was investigated by comparing results of the column settling tests conducted with Mobile Harbor sediment. Initial slurry concentrations of 58, 108 and 155 g/ℓ were tested. The test data were analyzed using the initial port sample as the initial supernatant concentration, as discussed above, and a depth of averaging of 1 ft. The reduced data for all three tests are summarized in Table 3. Curves were fit to the data sets and are shown in Figure 7. The results show that the suspended solids remaining increase as the test slurry concentration increases, as shown in Figure 7. Greater slurry concentrations produce smaller void spaces and greater upflow water velocities in the pores, expelling more solids. For example, at a retention time of 24 hr, the predicted supernatant suspended solids concentration is 26 mg/ℓ for an initial slurry concentration of 155 g/ℓ, but only 13 mg/ℓ for 58 g/ℓ. This magnitude of difference shows that the initial slurry concentration for the test should be carefully selected. It is recommended that the initial slurry

Table 3

Supernatant Suspended Solids Remaining for Column Tests Conducted at Three Slurry Concentrations, Mobile Harbor Sediment

Slurry Concentration g/ℓ	Time hr	Removal Percentage	Remaining SS* (mg/ℓ)
58	1.25	6	118
	3.5	13	109
	7	49	64
	14	77	29
	24	90	13
	48	94	8
108	4	15	94
	7	46	59
	10	60	44
	22	76	26
	28	87	14
	46	91	10
155	3.5	5	171
	6	60	72
	9	68	58
	14	76	43
	27	85	27
	48	91	16

* SS = suspended solids.

concentration for the test be as close as possible to the anticipated field influent concentration. This recommendation is also consistent with the selection of initial slurry concentration for conducting modified elutriate tests.

Test replicability

34. The reproducibility of the column test data produced by the test procedures recommended above was determined by conducting a set of replicate column settling tests using sediment from Mobile Harbor. Three columns were simultaneously filled with slurry using a manifold device to assure that essentially equal concentrations were placed in the columns. The initial slurry concentrations were 56 g/ℓ. Samples were taken from all three columns at 2, 4, 8, and 24 hr. The resulting concentration profiles are shown in Figure 8. The plotted points are labeled A, B, or C indicating the test replicates. The plotted data show that there was little difference in the replicate tests. Small differences always occur because of experimental error

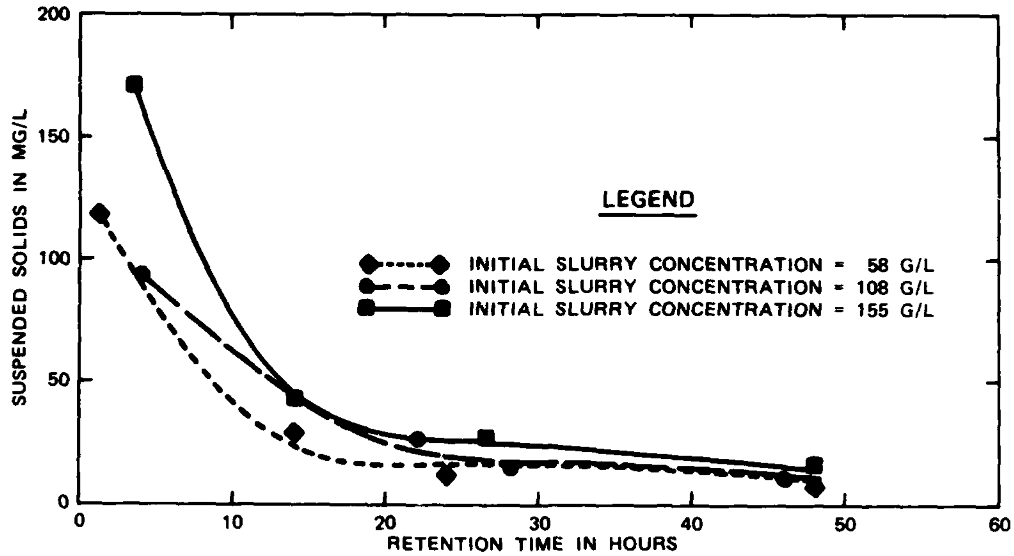

Figure 7. Relationship of predicted suspended solids concentration versus retention time for various initial slurry concentrations, Mobile Harbor column tests

in sampling and gravimetrically determining small concentrations of suspended solids. Furthermore, since some degree of judgment is normally required when drawing concentration profiles, the curves resulting from the three tests are practically identical. It is therefore apparently not necessary to perform more than one column settling test solely for purposes of predicting the effluent suspended solids concentration.

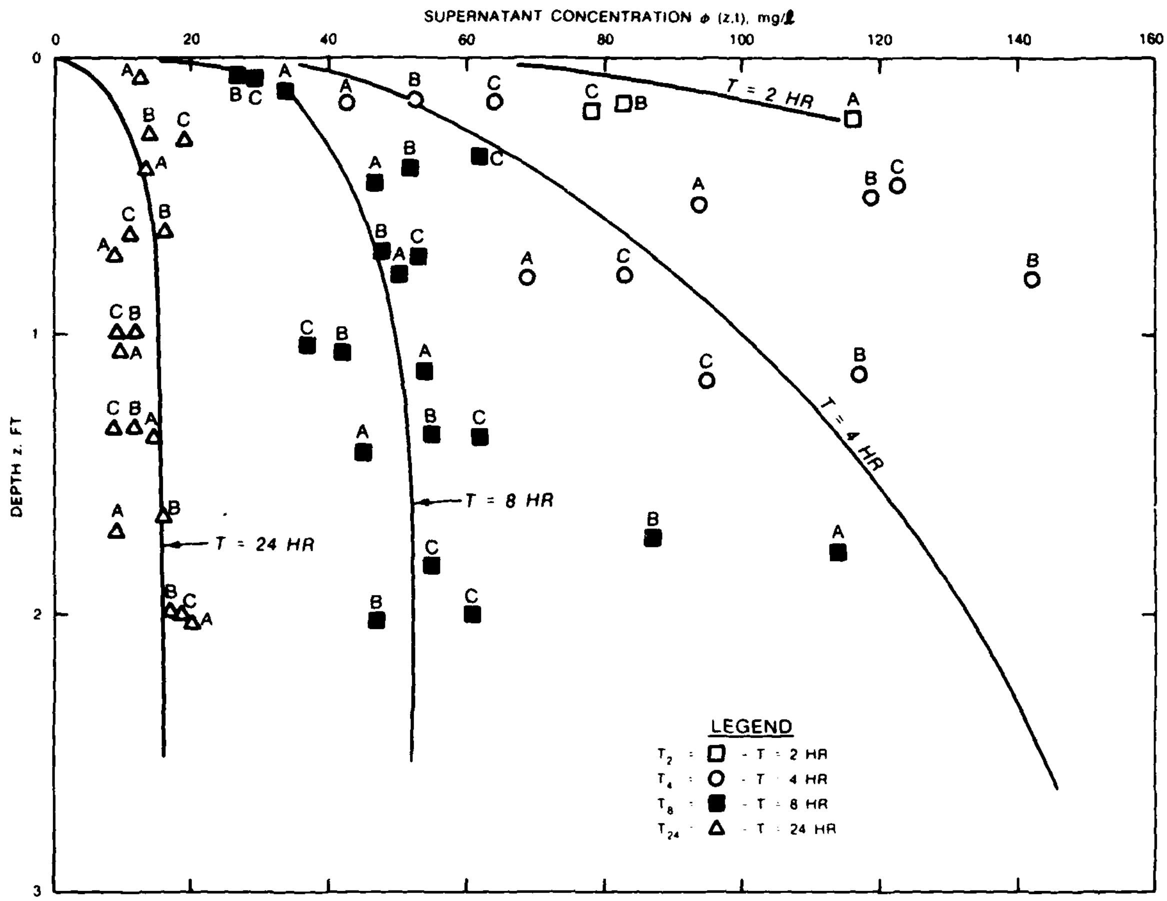

Figure 8. Concentration profile diagram for replicate column tests, Mobile Harbor

PART IV: COMPARISON OF LABORATORY ESTIMATES AND MEASURED FIELD DATA

Field Data

35. Comparisons of effluent suspended solids concentrations predicted using the modified column test and the data analysis procedure described above with mean measured field values were made for confined disposal areas at five sites. These sites were Mobile Harbor, Alabama; Savannah Harbor, Georgia; Norfolk Harbor, Virginia; Black Rock Harbor, Connecticut; and Kings Bay, Georgia. The mean field effluent suspended solids concentrations, mean retention times as determined by dye tracer tests, and mean ponding depths for the five disposal areas are tabulated in Table 4. The variables were measured by the best methods available at the time and appropriate for field conditions, but are recognized as somewhat imprecise. A full description of the field data collection was given by Palermo and Thackston (1988).

Column Tests

36. Column settling tests were conducted on samples from each site for the purpose of developing a relationship between predicted effluent suspended solids and retention time. Tests were conducted on grab samples of sediments and water from the sites where the dredges were operating at the time that the field sampling was begun. The sediment samples were mixed with site water to concentrations approximating the known field mean influent concentrations. The full details of the sampling program were described by Palermo (1986). The initial slurry concentrations for each test are tabulated in Table 4. Samples were extracted at side ports as soon as the interface cleared the ports. Data were analyzed as previously described using the modified McLaughlin analysis. The suspended solids concentrations remaining above the depths corresponding to the known mean ponded depths in the immediate vicinity of the weirs for the respective sites were determined for each time of sampling. Exponential curves of suspended solids as a function of time were fit to the data, and the predicted values for effluent suspended solids corresponding to the known mean retention times of the five disposal areas, as

Table 4

Comparison of Suspended Solids Concentrations from Column Settling

Tests with Mean Effluent Values

Site	Test Slurry Concentration g/ℓ	Approximate Ponded Area acres	Approximate Mean Depth ft	Mean* Field Retention Time hr	Mean Field Suspended Solids mg/ℓ	Lab Column Suspended Solids mg/ℓ	Ratio, Field to Lab	Settling Efficiency Adjustment Factor**	Predicted Suspended Solids mg/ℓ	Ratio, Predicted to Field
Mobile	99	40	1	12	40	33	1.21	2.0	66	1.65
Savannah	99	50	>2	53	75	85	0.88	1.5	128	1.70
Norfolk	122	600	>2	41	202 (high wind)	20	10.10	--	--	--
					35 (low wind)	20	1.75	2.0	40	1.14
Kings Bay	97	380	1	75	50	22	2.27	2.5	55	1.10
Black Rock	57	<1	<1	8	173	84	2.06	2.0	168	0.97

* Field mean retention was determined by dye tracer with the exception of the Kings Bay site. For this site, the mean retention time was estimated by applying a hydraulic efficiency factor of 2.25 to the estimated theoretical retention time. A more accurate method is now available and is described in Appendix A.

** Adjustment factor for settling efficiency and resuspension selected from Table 5.

Total surface area ponded for the Savannah site was approximately 400 acres. However, a majority of this area was involved in overland flow. The area ponded to depths of 2 ft or greater was limited to approximately 50 acres immediately in front of the weir. The selected resuspension factor for this site corresponds to a ponded areas less than 100 acres and ponded depth greater than 2 ft.

determined by dye tracer tests, were determined. Results for each area are tabulated in Table 4.

Adjustment Factors for Turbulence and Resuspension

37. The refined approach for prediction of effluent suspended solids described above assumes that the confined disposal area is well designed and operated, the weir has sufficient crest length, and ponding conditions are such that resuspension of settled material is avoided. Good design assures adequate ponded surface area and sufficient storage for the zone settling process to concentrate the dredged material, if the entire slurry mass undergoes zone settling. However, the mean field effluent concentration for well-designed and well-operated sites would likely be higher than that indicated by quiescent laboratory tests. Quiescent conditions are optimum for efficient settling, but are impossible to achieve in the field. Flow of water through the area produces advective velocities, which generate turbulence. In addition, wind produces surface shear, which induces even higher velocities. These effects decrease settling efficiency and increase field effluent suspended solids over lab column suspended solids for identical settling times. In addition, some solids that settle when winds are light are resuspended when winds rise. The data in Table 4 confirm this.

38. Plots of means and standard deviations for measured field effluent suspended solids concentrations and values predicted using the column test procedure described above are shown plotted in Figure 9. These data graphically show that the measured mean field concentration of suspended solids is higher than the predicted concentration from lab column tests for four of the five comparisons. The predicted values of effluent suspended solids using the modified McLaughlin analysis described can therefore be considered a minimum value that can be achieved in the field under the best possible conditions for settling (i.e. little turbulence and little or no solids resuspension because of wind effects). The comparison of predicted values from the column tests and mean measured field concentrations in Table 4 shows that an adjustment for turbulence and anticipated solids resuspension caused by wind would be appropriate for most cases. Even though the field data available were limited, the range of ratios of field values to predicted values shown in Table 4 is a good

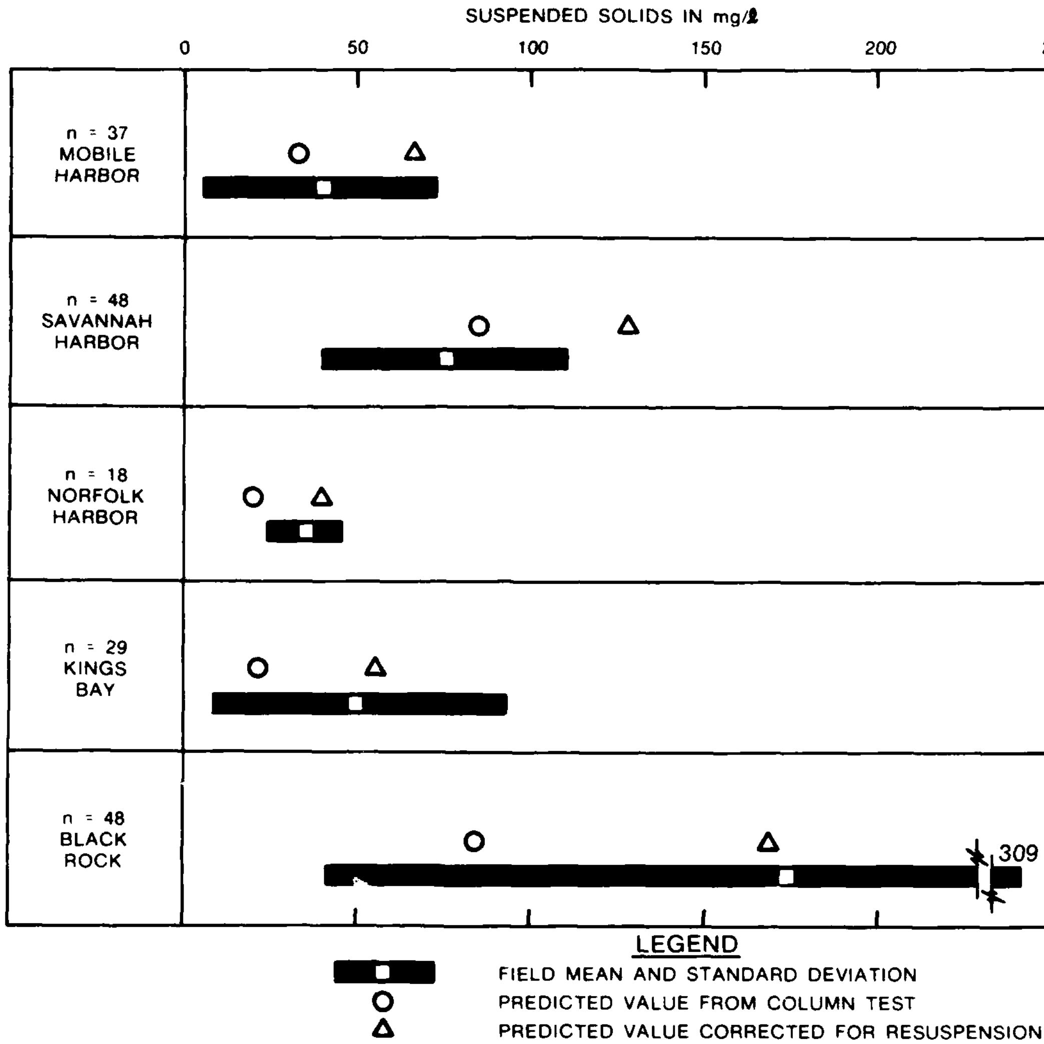

Figure 9. Plot of means and standard deviations for field effluent suspended solids concentrations and predicted values from column settling tests

indicator of appropriate factors for adjusting the laboratory-measured values for anticipated turbulence and solids resuspension to produce a predicted value.

39. A reasonable approach in selecting appropriate settling efficiency adjustment factors would be based on both anticipated ponded areas and anticipated ponding depths. The level of turbulence is related to advective flow velocities, which are inversely proportional to ponded surface area and ponded depth. However, wind effects usually influence flow velocities and turbulence

in shallow confined disposal areas to a greater degree than flow rate and ponded volume. Also, as the ponded area increases, fetch distances for possible wind-induced waves increase, and the potential for solids resuspension also increases. As ponded depths and widths increase, the advective velocity decreases. Also, increasing depth reduces the influence of wave action at the interface, and the potential for solids resuspension decreases.

40. Field observations of conditions at all the sites indicated light to moderate wind, with the exception of the Norfolk site. Storm conditions were experienced at this site during early sampling efforts, and the effluent suspended solids data that were collected for that sampling period are shown separately in Table 4. The Norfolk data for storm conditions indicate that measured field effluent suspended solids can be higher than the values predicted by the column test by a factor of 10. However, designing for such extreme conditions would be overly conservative during almost all of the operating time.

41. The remainder of the cases shown in Table 4 indicate that the ratios of field-to-laboratory values vary from slightly less than 1 to 2.27. A set of recommended settling efficiency adjustment factors was selected based on these data. The variables were ponded area (less than or greater than 100 acres) and ponded depth (less than or greater than 2 ft). The recommended adjustment factors vary from 1.5 to 2.5 and are presented in Table 5. These settling efficiency adjustment factors are considered sufficiently conservative for purposes of disposal area evaluations under normally encountered wind conditions.

Table 5

Recommended Settling Efficiency Factors for the Zone Settling Case for Various Ponded Areas and Depths

Anticipated Ponded Area	Anticipated Average Ponded Depth: Less than 2 ft	Anticipated Average Ponded Depth: 2 ft or Greater
Less than 100 acres	2.0	1.5
Greater than 100 acres	2.5	2.0

42. The values of suspended solids from the lab column tests were corrected for settling efficiency using the appropriate values selected from Table 5. The adjusted predicted effluent suspended solids concentrations are shown in Table 4 and are also plotted in Figure 9. In all cases, the adjusted predicted values are conservative estimates of the effluent suspended solids concentration, with an average ratio of predicted-to-field values of 1.31. The adjustment factors for settling efficiency described above are based on engineering judgment and limited field and laboratory data. For this reason, it is recommended that the procedures be refined as appropriate as column test and field data from additional sites become available.

PART V: RECOMMENDATIONS

43. Based on the results of testing sediments from Mobile Harbor (composite), Black Rock Harbor, and Yellow Creek, the performance of flocculent settling tests and the analysis of the data using the McLaughlin approach are recommended for predicting the suspended solids concentrations in the effluent from confined disposal areas. For cases in which flocculent settling governs the entire slurry mass, the procedures recommended by Montgomery (1978) may be directly applied.

44. For cases in which zone settling describes the settling behavior of the slurry mass, the modified column test procedures described above should be used to obtain flocculent settling data for the volume of semi-clarified supernatant above the interface, and the modified McLaughlin approach should be used to analyze the data. The column tests should be run in 8-in.-diam ported columns at slurry concentrations equal to the anticipated field influent concentrations.

45. Suspended solids concentrations from the quiescent laboratory column tests should be adjusted upward to account for poorer settling efficiency resulting from turbulence and solids resuspension under field conditions. Based on comparisons of column predictions and measured field data from Mobile Harbor, Savannah Harbor, Norfolk Harbor, Black Rock Harbor, and Kings Bay, settling efficiency adjustment factors ranging from 1.5 to 2.5 result in conservative predictions of effluent suspended solids concentrations and are recommended. Detailed step-by-step procedures are given in Appendix A.

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APPENDIX A: RECOMMENDED COLUMN TEST PROCEDURES AND EXAMPLE CALCULATIONS

Recommended Column Test Procedures

1. Settling tests, performed in 8-in.-diam ported columns as shown in Figure A1, are necessary to provide data for design or evaluation of disposal areas for retention of suspended solids. These tests are designed to define the flocculent or zone settling behavior of a particular sediment and to provide information concerning the volumes occupied by newly placed layers of dredged material. The test procedures have been refined to obtain data for use in predicting the concentration of suspended solids in the effluent for both the flocculent and zone settling case.

2. Sedimentation of freshwater slurries of solids concentrations less than 100 g/ℓ can generally be characterized by flocculent settling. As solids concentrations exceed 100 g/ℓ, the sedimentation process may be characterized by zone settling properties in which a clearly defined interface is formed between the clarified supernatant water and the more concentrated settled material. Zone settling also describes the process when the sediment/water salinity is greater than 3 ppt. The studies described in the main text have shown that flocculent settling describes the behavior of suspended solids in the clarified supernatant water above the sediment/water interface for slurries exhibiting an interface.

Apparatus

3. A settling column such as shown in Figure A1 should be used. The test column depth should approximate the effective settling depth of the proposed disposal area. A practical limit on the depth of the test is 6 ft. The column should be at least 8 in. in diameter with interchangeable sections and with sample ports at 1-ft or closer intervals in the lower 3 ft and at 1/2-ft or closer intervals in the upper 3 ft. The column should have provisions to bubble air from the bottom to keep the slurry mixed during the column filling period or to recirculate slurry from the bottom of the column to the top.

Flocculent settling test procedure

4. Test data required to design or evaluate a disposal area in which flocculent settling of the slurry occurs and to predict the concentration of suspended solids in the effluent can be obtained using the design procedures

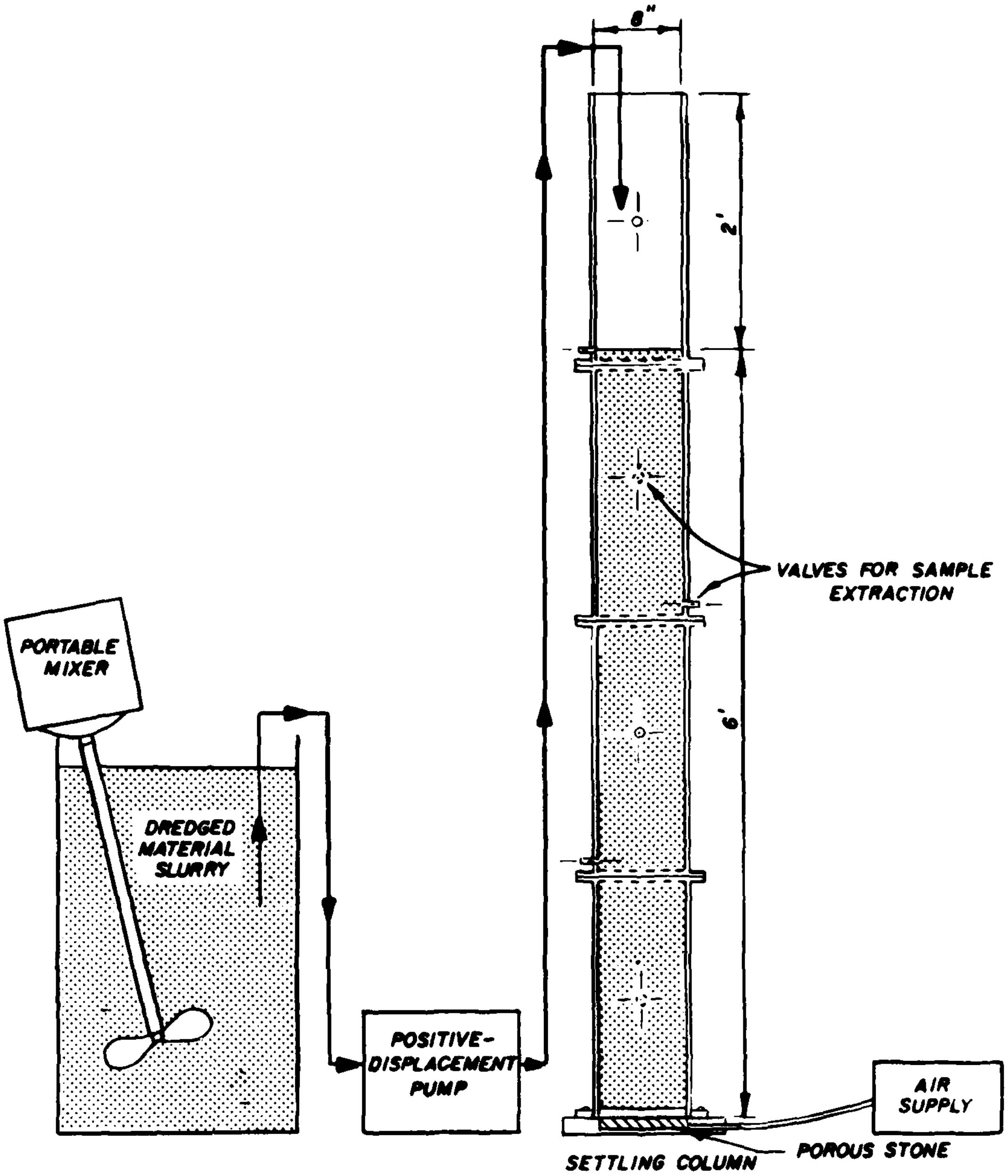

Figure A1. Schematic of apparatus for column settling tests (after Montgomery 1978) described by Montgomery (1978)* and Palermo, Montgomery, and Poindexter (1978). These procedures allow the prediction of the concentration of the suspended solids in the effluent, $[SS_{eff}]$, as a function of retention time.

Zone settling test procedure

5. Information required to design or evaluate a disposal area in which zone settling of the slurry occurs can be obtained by a zone settling test (Montgomery 1978; Palermo, Montgomery, and Poindexter 1978) performed on sediment slurry at a concentration equal to the expected mean field influent concentration. This test should be continued for a period of at least 15 days to provide data for estimating disposal area volume requirements. This test is also used to obtain data for the prediction of effluent suspended solids concentrations by defining the flocculent settling behavior of the supernatant suspended solids. The stepwise procedure for this test is described below.

6. Step 1--slurry preparation and loading. Mix the sediment slurry to the desired suspended solids concentration in a container with sufficient volume to fill the test column. The test should be performed at the concentration selected to represent the anticipated concentration of the dredged material influent, C_i. Field studies indicate that for maintenance dredging in fine-grained material, the disposal area influent concentration will average about 150 g/ℓ. This value may be used for C_i if no better data are available.

7. Step 2--settling and sampling. Begin extracting samples from the side ports for determination of suspended solids concentration. For sediments exhibiting zone settling behavior, an interface will form between the more concentrated settled material and the semi-clarified supernatant water. The first sample should be extracted immediately after the interface has fallen sufficiently below the uppermost port to allow extraction without withdrawing solids from below the interface. This sample can usually be extracted within a few hours after initiation of the test, depending on the initial slurry concentration and the spacing of ports. Record the time of extraction, port height, and height of the fluid surface for each port sample taken. As the interface continues to fall, extract samples from all ports above the interface at regular time intervals. Substantial reductions of suspended solids will occur during the early part of the test, but reductions will lessen at

* See References at the end of the main text.

longer retention times. Therefore, the sampling intervals can be extended as the test progresses. A typical sequence of intervals would be 2, 4, 8, 12, 24, 48, 96 hr, etc. The samples should continue to be taken throughout the 15-day test or until the suspended solids concentration of the extracted samples shows no decrease.

Data analysis

8. For the flocculent settling case, the procedures for data analyses given by Montgomery (1978) and Palermo, Montgomery, and Poindexter (1978) may be used. For the zone settling case, flocculent settling describes the settling behavior in the supernatant water above the interface. Therefore, a flocculent settling data analysis procedure as outlined in the following paragraphs is required. Example calculations are also shown in the following paragraphs, using data from a column test conducted on sediment from Savannah Harbor. This test was conducted at an initial slurry concentration of 99 g/ℓ according to the procedures mentioned above.

9. The steps in the data analysis are as follows:

a. Step 1. Arrange the flocculent settling test data from the laboratory test as shown in Table A1, and compute values of the depth of sampling below the fluid surface, z. In computing the fractions remaining, ϕ, the concentration of the first port sample is considered the initial concentration, SS_o.

b. Step 2. Plot the values of fractions remaining $\phi(z,t)$ and z using the data from the table as shown in Figure A2 forming a concentration profile diagram. Concentration profiles should be plotted for each time of sample extraction.

c. Step 3. Use the concentration profile diagram to graphically determine percentages removed, R, for the various time intervals, averaged over any desired ponding depth, D_{pw}. This is done by graphically determining the areas to the right of each concentration profile and its ratio to the total area above the depth D_{pw}. The removal percentage R is

$$R = \frac{\text{Area to right of profile}}{\text{Total area}} (100) \qquad \text{(A1)}$$

d. Step 4. Compute the percentage remaining as simply 100 minus the percentage removed:

$$P = 100 - R \qquad \text{(A2)}$$

Table A1

Selected Observed Flocculent Settling Data, Savannah Harbor Sediment

Sample Extraction Time T, hr	Port Height ft	Head Height ft	Depth of Sample Extraction z, ft	Total Suspended Solids mg/ℓ	Fraction of Initial, ∅ percent
22	4.7	4.99	0.29	$SS_o = 143$	100
48	4.7	4.95	0.25	77	54
48	4.3	4.95	0.65	90	63
48	4.0	4.95	0.95	90	63
48	3.7	4.95	1.25	78	55
48	3.3	4.95	1.65	106	74
360	4.7	4.73	0.03	30	21
360	4.3	4.73	0.43	30	21
360	4.0	4.73	0.73	33	23
360	3.7	4.73	1.03	30	21
360	3.3	4.73	1.43	29	20
360	3.0	4.73	1.73	32	23
360	2.7	4.73	2.03	31	22

e. Step 5. Compute values for suspended solids for each time of extraction:

$$SS_t = P_t \, SS_o \tag{A3}$$

Arrange the data as shown in Table A2.

f. Step 6. Plot a relationship for remaining suspended solids concentration versus time using the value for each time of extraction as shown in Figure A3 in Example 1. An exponential curve fitted through the data points is recommended.

10. This curve may be used for the prediction of effluent suspended solids concentrations under good settling conditions for any estimated mean field retention time. Simply enter the curve with the estimated mean field

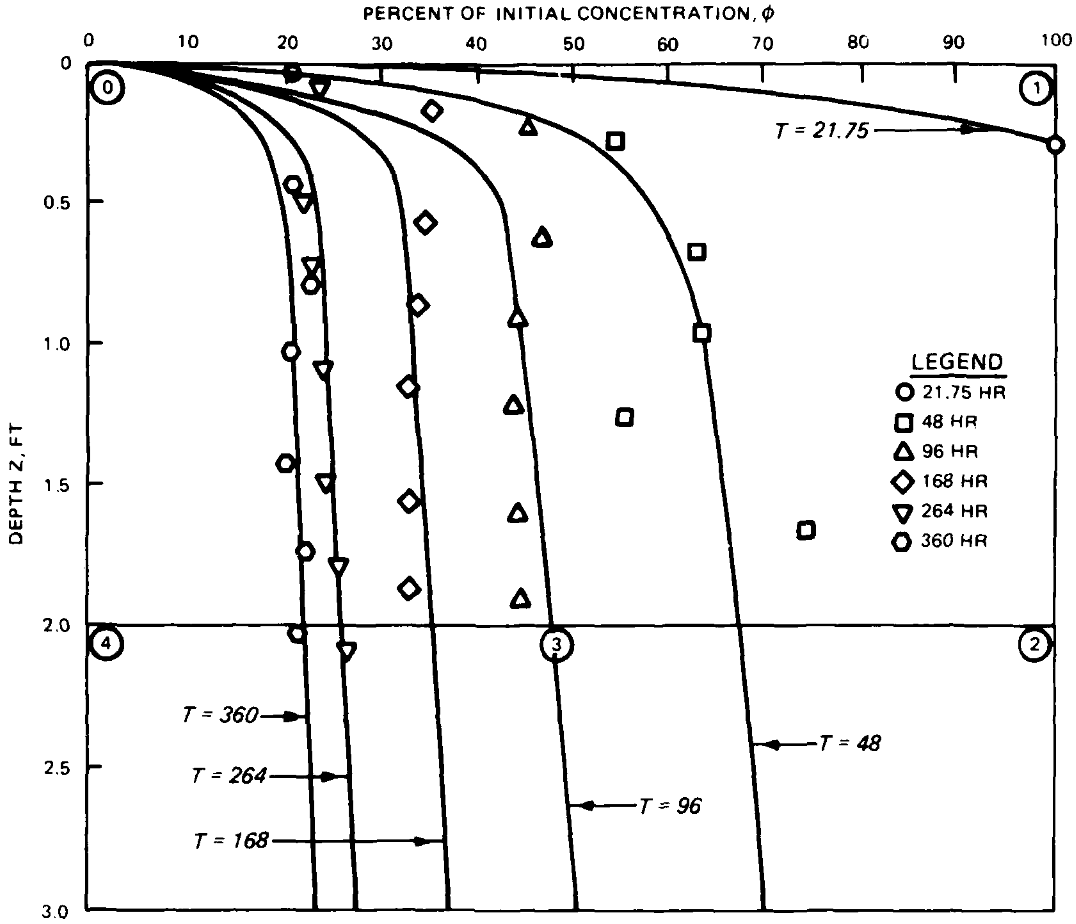

Figure A2. Concentration profile diagram, Savannah Harbor sediments

Table A2

Percentage of Initial Concentration and Suspended Solids Concentration Versus Time, Savannah Harbor Sediment

Sample Extraction Time, t, hr	Removal Percentage at t	Remaining Percentage at t	Suspended Solids mg/ℓ
22	3	97	139
48	40	61	86
96	61	39	56
168	70	30	43
264	78	22	32
360	81	19	27

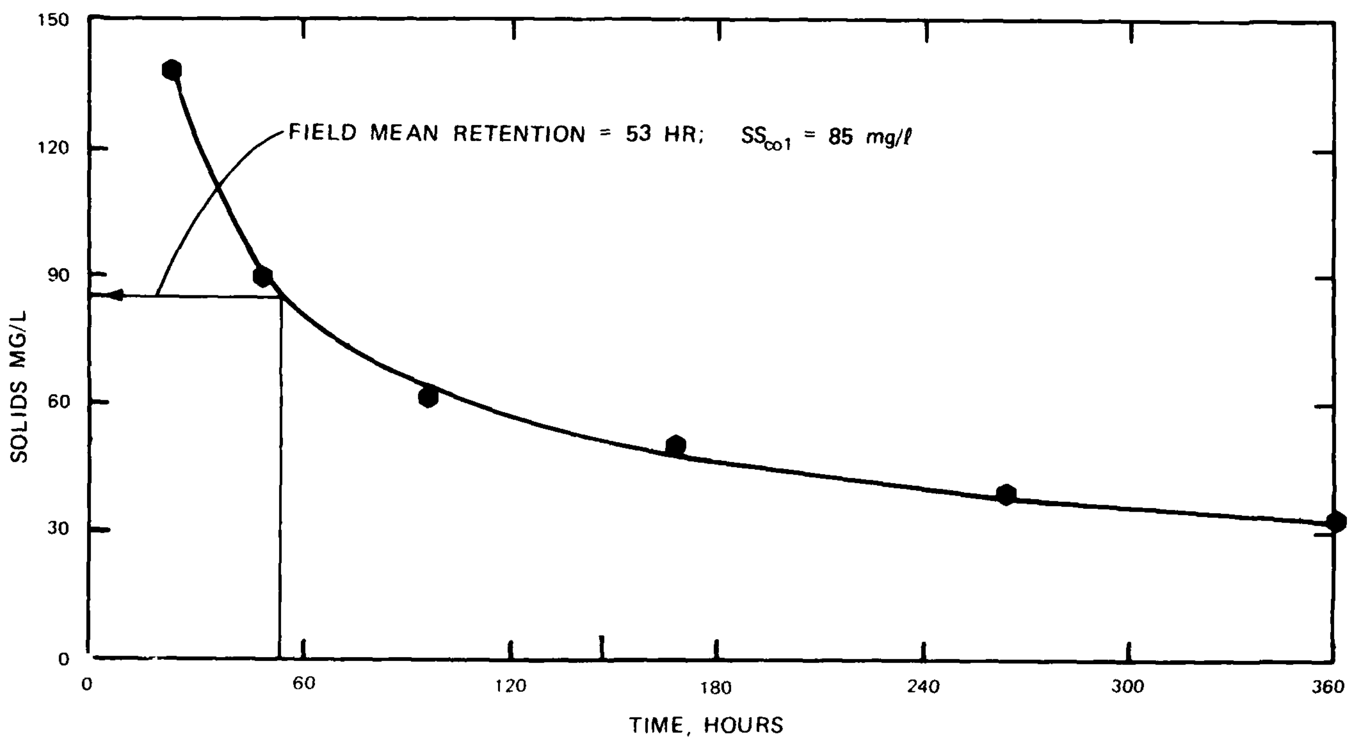

Figure A3. Plot of supernatant suspended solids concentration versus time from column settling tests, Savannah Harbor sediments retention time, T_d , and select the value of suspended solids as predicted by the column test, SS_{col} . Guidance for adjusting the value derived from the column test for anticipated field settling efficiency and for estimating mean field retention time is given in the following paragraphs.

Determination of Effluent Suspended Solids Concentration

11. A prediction of the concentration of total suspended solids in the effluent must consider the anticipated mean retention time in the disposal area and must account for possible turbulence and resuspension of settled material because of wind effects. The relationship of supernatant suspended solids versus time developed from the column settling test is based on quiescent settling conditions found in the laboratory. The anticipated mean retention time in the disposal area under consideration can be used to determine a predicted suspended solids concentration from the relationship. This predicted value can be considered a minimum value that can be achieved in the field assuming little or no turbulence or resuspension of settled material. However, an adjustment for anticipated poorer settling caused by turbulence and resuspension is appropriate for typical conditions in dredged material containment areas. The minimum expected value and the value adjusted for turbulence and resuspension would provide a range of anticipated poorer settling and suspended solids concentrations for use in predicting the total concentrations of contaminants in the effluent. The value adjusted for anticipated poorer settling and resuspension is

$$[SS_{eff}] = [SS_{col}] \times SEF \tag{A4}$$

where

$[SS_{eff}]$ = suspended solids concentration of effluent considering anticipated resuspension, milligrams suspended solids/litre of water

$[SS_{col}]$ = suspended solids concentration of effluent as estimated from column settling tests, milligrams of suspended solids/litre of water

SEF = settling efficiency adjustment factor selected from Table 5 (see main text)

Table 5 summarizes recommended settling efficiency adjustment factors based on comparisons of suspended solids concentrations as predicted from column settling tests and those obtained from field experiments from a number of sites with varying site conditions. For dredged material exhibiting flocculent settling behavior (freshwater), the concentration of particles in the ponded supernatant water is on the order of 1 g/ℓ or higher. The turbulence and resuspension resulting from normal wind conditions will not significantly increase the concentration. Therefore, an adjustment would not be required for the flocculent settling case.

Determination of Field Mean Retention Time

12. Estimates of the mean field retention time for expected operational conditions are required for selecting appropriate settling times in the modified elutriate test and for determination of suspended solids concentrations in the effluent. Estimates of the mean retention time must consider both the theoretical volumetric retention time $T = V/Q$ and the hydraulic efficiency of the disposal area, defined as the ratio of mean retention time to theoretical retention time. Mean field retention time, $\bar{t}_d$, can be estimated for given flow rate and ponding conditions by applying a hydraulic efficiency correction factor to the theoretical detention time, T , as follows:

$$\bar{t}_d = \frac{T}{(\mathrm{HECF})} \tag{A5}$$

where

$\bar{t}_d$ = mean retention time, hours

T = theoretical retention time, hours

HECF = hydraulic efficiency correction factor (HECF > 1.0) defined as the inverse of the hydraulic efficiency

The theoretical retention time is

$$T = \frac{V_P}{Q_i} 12.1 = \frac{A_P D_P}{Q_i} (12.1) \tag{A6}$$

where

T = theoretical retention time, hours

V_p = volume ponded, acre-feet

A_p = area ponded, acres

D_p = average depth of ponding, feet

Q_i = average influent rate, cubic feet per second

12.1 = conversion factor acre-feet/cubic feet per second to hours

13. The hydraulic efficiency correction factor, HECF , can be estimated by several methods. The most accurate estimate is made possible from field dye tracer data previously obtained at the site under operational conditions similar to those for the operation under consideration. Guidance for conducting such field tests is presented by Palermo (1984). This approach can be considered only for existing sites.

14. In the absence of dye tracer data or values obtained from other theoretical approaches, Shields et al. (1987) showed that the HECF can be estimated from Equation A7.

$$\frac{\bar{t}}{T} = 0.84 \left[1 - \exp\left(-0.59 \frac{L}{W}\right)\right] \tag{A7}$$

Example Calculations

Project information

15. Dredged material from a maintenance project was placed in an existing disposal site at Savannah Harbor. The site was ponded over an area of approximately 50 acres. The design calculation using procedures described by Montgomery (1978) and Palermo, Montgomery, and Poindexter (1978) indicated that the surface area was adequate for effective sedimentation if a minimum ponding depth of 2 ft were maintained. The dredging equipment and anticipated pumping conditions resulted in a mean flow rate of approximately 30 cfs. A dye tracer test was run at this disposal site, and the mean field retention time was 53 hr. Sampling of influent from the dredge pipe indicated that the influent solids concentration was approximately 107 g/ℓ.

16. The quality of effluent was predicted using the procedures outlined above.

Column settling tests

17. Samples from the dredging area were homogenized into a composite for column settling tests. The test used for prediction of effluent suspended solids was run at a slurry concentration of 99 g/ℓ, equivalent to the influent slurry concentration. The interface formed early in the test, but the settling velocity was slow, and the initial port sample was taken at 22 hr. Samples were extracted from all cleared ports at 22, 48, 96, 168, 264, and 360 hr. Partial data for the solids concentrations and calculated values of z are shown in Table A1. The concentration profile diagram was then constructed from the data as shown in Figure A2. Ratios or percentages removed as a function of time were then determined graphically using the step-by-step procedure described previously.

18. Since an interface formed in the test, the slurry was undergoing zone settling. Therefore, the initial supernatant solids concentration, SS_o, was assumed to be equal to the concentration of the first port sample taken, 143 mg/ℓ. An example calculation for removal percentage for the concentration profile at $T = 96$ hr and $D_{pw} = 2.0$ ft using Equation A4 is as follows:

$$R_{96} = \frac{\text{Area right of the profile}}{\text{Total area}} (100) = \frac{\text{Area 01230}}{\text{Area 01240}} (100) = 61\% \tag{A8}$$

The areas were determined by planimeter. The percentage remaining at $T = 96$ hr is found using Equation A2.

$$P_{96} = 100 - R_{96} = 100 - 61 = 39\% \tag{A9}$$

The values for the suspended solids remaining are found using Equation A3.

$$SS_{96} = P_{96}\, SS_o = \frac{37}{100} (143) = 56 \text{ mg/ℓ} \tag{A10}$$

Values at other times were determined in a similar manner. The data were arranged in Table A2. An exponential curve fitted to the data for total suspended solids versus retention time is shown in Figure A3.

Prediction of effluent
suspended solids concentration

19. A value for effluent suspended solids can be determined for quiescent settling conditions using the column test relationship. In this case, the field mean retention time of 53 hr corresponds to a suspended solids concentration of 85 mg/ℓ, as shown in Figure A3. This value should be adjusted for anticipated field settling efficiency using the factors shown in Table 5. In this case, for a surface area less than 100 acres and average ponding depth of 2 ft, the settling efficiency adjustment factor is 1.5. The predicted total suspended solids concentration in the effluent is calculated using Equation A4 as

$$[SS_{eff}] = [SS_{col}] \times SEF = 85 \text{ mg}/\ell \times 1.5 = 128 \text{ mg}/\ell \qquad \text{(A11)}$$